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Performance Evaluation of A Typical Energy Monitoring System for Steam Flow in Buildings

Building Equipment Division
Center for Building Technology
U.S. Department of Commerce
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Engineering Laboratory
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PERFORMANCE EVALUATION OF A TYPICAL ENERGY MONITORING SYSTEM FOR STEAM FLOW IN BUILDINGS

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ABSTRACT

Some important design features and measurement techniques are discussed for determining energy rates in building systems flowing steam. Emphasis is on use of differential pressure (ΔP) type flowmeter systems, where only ΔP pressure and temperature instrumentation can receive direct calibration. The role of systematic and random errors in measurement of building energy is discussed and an appropriate method is given for estimating the uncertainty in the energy consumed. An illustrative calculation of uncertainty in accumulated energy used for a one year period is given from estimated operating data for one of the NBS laboratory buildings. The uncertainty is estimated to be 3.2 percent for a two-meter (series) configuration and 4.3 percent for a single meter (high range meter) configuration.

Key Words: Building energy monitoring; energy measurement; steam consumption measurement; uncertainty estimate.

CONVERSION FACTORS TO METRIC (SI) UNITS

Physical Quantity	Symbol	To Convert From	To	Multiply By
Acceleration	g	ft/s^2	m/s^2	3.048×10^{-1}
Density	ρ	lb/ft^3	kg/m^3	1.602×10^{1}
Energy rate	E	Btu/hr	J/s	2.931×10^{-1}
Enthalpy	h	Btu/lb	J/kg	2.326×10^{3}
Length	L	in.	m	2.540×10^{-2}
Mass flowrate	M	lb/hr	kg/s	1.260×10^{-4}
Pressure	P	psi	Pa	6.895×10^{3}
	h_w	in. H_2O	Pa	2.486×10^{2}
Specific heat	c_p	Btu/(lb·°F)	J/(kg·K)	4.187×10^{3}
Temperature	T	°F	°C	$t_c = (t_f - 32)/1.8$
Viscosity	μ	lb/(ft·s)	Pa·s	1.488

Note: English units are customary in fluid measurements and are used in this paper.

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I. INTRODUCTION

During the late 1970's large efforts toward improving energy utilization in buildings were made in various sectors: industrial, residential, commercial, and governmental. Thus, there is a need for accurately measuring and monitoring energy consumed. In determining costs or energy savings, often an estimate of or knowledge of the inaccuracy or uncertainty of the energy measurement is important. For example, a claimed energy savings or decrease in consumption of, say, 8.0 percent due to a particular operating procedure or equipment change may actually be greater or less than this. The uncertainty is never known exactly. However, from knowledge of the measuring systems, including instrumentation and data processing equipment and procedures, an estimate of the uncertainty of the resulting energy measurements can be made through error analysis. Then a statement such as "an energy savings of 8.0 $\pm$ 2.0 percent for the period . . ." can be made with a specified degree of confidence, where $\pm$ 2.0 percent refers to the overall uncertainty of the measurement process. For completeness, from a measurement point of view, the kinds of error (systematic and/or random) making up the uncertainty and their magnitudes would be included.

The most accurate measurements of the energy consumed by building systems which employ flowing fluids such as steam, hot water or chilled water result from measurements in which each measuring system is calibrated directly under conditions the same as those which exist when on line. This means, for example, steam flowrate would be measured with a metering system calibrated directly at a separate calibration facility flowing steam at a specified line temperature and pressure. An alternate method would involve a transfer reference meter system calibrated directly and subsequently installed on line to serve as the calibration reference for

the (working) meter system. The uncertainty associated with the direct calibration or transfer systems (which combine the effects of many individual errors) would serve as the basis for assigning an uncertainty to measurements made with the working meter. However, the direct calibration approach may require facilities not readily available, or it may be too costly or time consuming particularly when large numbers of meters are involved. Also, the adequate installation of a transfer reference meter system into the building lines may be impractical or impossible in existing building systems. In fact, adequate installation of the working meter alone is often difficult. Installation and measurement of other parameters such as static pressure, differential pressure, single point temperature, and differential temperature usually offer less difficulty from a physical point of view.

Thus, indirect methods may be more practical and useful in estimating the uncertainty of energy measurements. In one approach using differential pressure (ΔP) type flowmeters, the flow characteristics of the (working) meter primary element (orifice, venturi, or nozzle) are determined from published data for flow coefficients and fluid expansion factors instead of relying on direct calibration procedures. All other sensors and transducers (temperature, pressure and differential pressure transmitters) receive direct calibration. Error analysis then is used to estimate an overall uncertainty based on individual errors due to the meter flow characteristics and transducer and sensor calibrations. This paper includes a discussion of this approach as applied to measurements of energy used at one of the laboratories at the National Bureau of Standards (NBS), Gaithersburg, Maryland.

In the program at NBS, the energy consumed by the heating, ventilating and air conditioning (HVAC) systems is being monitored in the Materials Research Building for the purpose of evaluating energy savings of various operational and control techniques for NBS general purpose laboratories. The scope of the program includes monitoring HVAC equipment status, space temperature, heat transfer medium temperature and flowrate, and building energy consumption in the form of steam, chilled water and electricity.

Measurements include building supply steam flowrate, temperature and pressure, and condensate temperature; building supply chilled water flowrate (CHW flow) and temperature differential (CHW ΔT); and reheat hot water flowrate (HW flow) and temperature differential (HW ΔT) for the heat exchangers. Also, for 3 of 10 air conditioning units (ACU), the reheat HW flow and ΔT, the CHW flow and ΔT, and the preheater steam supply flowrate and temperature, and condensate temperature are measured. Data is accumulated and processed through an on-line general purpose digital computer system. This system is designed for monitoring energy in all main buildings at NBS, Gaithersburg.

The purpose of this paper is (1) to review some important design considerations for instrumenting energy monitoring systems with emphasis on systems that measure steam flow, and (2) to present a method of estimating the uncertainty of energy usage using an illustrative calculation for building steam consumption covering a period of one year. The number of variables is quite large, and a complete list is included in Appendix D. The accuracy calculations discussed are currently not computer based.

This paper is written as an aid or guide for the reader who may be faced, for the first time, with the task of making similar measurements. Thus, the nature of uncertainty as applied to this measurement situation is discussed briefly.

II. DESIGN CONSIDERATIONS

Establishing an energy monitoring program will include a statement of purpose or technical goal, a summary of building design and energy systems, an analysis of any existing building operating data, and a selection of utility parameters and energy handling systems to monitor. Once these decisions have been made, design of the measurement system can begin. Starting with design of individual measuring systems, this may include instrument and hardware selection, determination of computational, data capacity and instrumentation accuracy requirements, and consideration of calibration and operating procedures. Also, the data collection and processing systems need to be specified and selected. With a computer-based prototype system, data requirements and program scope often increase during the program so that it is wise and more economical to use a system on the "large side."

When an energy monitoring system is to be installed in new construction, this system should be considered an integral system along with other building systems. In this way, the location and installation of transducer systems, signal and power cables, and data processing equipment can all receive adequate attention. Such specific items as location of temperature sensors and wells, installation of sufficient straight pipe runs for flowmeters, provisions for inserting on line calibration transducers such as reference flowmeters, location of transducer or transmitter units for accurate signal sensing and adequate accessibility for maintenance and calibration usually all can be satisfied at reasonable costs. Satisfying all such requirements for systems installed in existing buildings is often expensive and difficult, or sometimes virtually impossible.

While the energy monitoring program for the existing Materials Research Building also includes metering chilled water and hot water flows as listed above, the fluid considered most difficult to measure is steam flow. Systems were in-

stalled in this building to measure steam building supply flowrate, temperature and pressure, condensate temperature, and for 3 of 10 ACU's, the preheater supply flowrate and temperature, and condensate temperature.

This discussion pertains to design considerations for the systems metering the building supply steam flows. The main points discussed are the meter installation, differential pressure (ΔP) measurement, and metering system calibration techniques.

1. Meter Installation. Steam at nominal 150 psig and nearly saturated enters the Materials Research Building through an 8-inch supply line and rises to the 4th floor, where its pressure is reduced to a nominal pressure of 27 psia and temperature of 290°F, i.e., about 45°F superheat. The steam then branches into two 5-inch lines.

The best flowmeter locations were in the two 5-inch lines from the standpoint of required straight pipe runs and accessibility. Initially, two reversed-type pitot-static tubes, one in each line, were installed. These have the advantages of easy and low cost installation. However, since installation of adequate plumbing to accommodate transfer reference flowmeters for in-line calibrations would be quite expensive and impractical in this building, and since the flow characteristics of such pitot-static tubes are not well known, each of these were later replaced by a square edge, thin plate, concentric orifice. The vortex shedder type meter was also seriously considered at this time but was not adopted because differential pressure transmitter equipment already installed with the pitot tubes was also suitable for use with the orifices. Each orifice plate was installed following ASME recommended procedures [1]*. These included installation of a suitable flow straightener upstream, and use

* Numerals in brackets refer to references listed at the end of the paper.

of recommended minimum lengths of straight pipe upstream and downstream of the orifice. Such "flow pattern" control is very important for accurate metering. Otherwise, transverse or swirling flow components can adversely influence the differential pressure sensed at the orifice, resulting in grossly inaccurate flowrate measurement. The importance of flow pattern control for accurate metering is sometimes not realized and proper installation of metering systems in existing building systems is often difficult.

2. Differential Pressure Measurement. In addition to a satisfactory meter installation, successful metering depends on accurate ΔP measurement across the flowmeter. The ingredients are selection of suitable transducer or transmitter and signal processing equipment, installation of transmitter and pressure sensing lines using "good practice" techniques, and continued maintenance of the system including transmitter and instrument calibration checks on a periodic basis as necessary. The importance of an accurate ΔP measurement cannot be overemphasized.

In selecting transmitter equipment, several points need consideration. Usually, the transmitter with the highest "accuracy" rating compatible with the application needs and dollars available tends to be selected, but transmitter characteristics covered under the term "accuracy" vary with the manufacturers. High stability and low hysteresis are essential characteristics. Also, performance shift due to changes in ambient temperature and line pressure level should be as low as possible. Highly linear transmitters may not be essential when used with digital computer systems since nonlinearities can be corrected through software. Also, fast dynamic response may not be important since operating conditions for building systems tend to change slowly.
The full scale differential pressure should be as large as practical compatible with allowable building system pressure losses, because accurate measurement of small differentials of a few inches of water full scale is difficult. Finally, when the flowrate range is larger than say 3:1, use of more than one transmitter

should be considered to avoid severe degradation of performance at part scale operation for transmitters rated on a full scale basis. For example, a transmitter rated at 0.5 percent full scale would only need produce a differential pressure measurement within 5 percent of reading at 10 percent full scale to still comply with its rated performance characteristic.

The ΔP transmitters selected for this application for all systems were an industrial type, using diffused silicon strain gages, namely Honeywell Models 41102 and 41105* with rated "accuracy" of 0.35 percent of adjusted span. In order to cover the nominal 10:1 flowrate range of 320 to 3200 lb/hr for building supply steam flow, two transmitters were used in each meter, one with a full scale rating of 105 inches of water at 68°F (in. H_2O), and one of 40 inches full scale with span adjusted to 8.0 inches. The range of 6.37 to 8.00 inches was used as an overlap region for transmitter checks under computer program control. One calibration constant was used for scaling each transmitter; thus no corrections were made for nonlinearity.

The pressure differential sensed by the transmitter should be exactly the same as that existing at the orifice meter. The interface between steam vapor and condensate in each pressure sensing line (leg) must be at the same height. Typical installation details for both horizontal and nonhorizontal pipe flow may be found in [1]. Possible troubles include air or vapor trapped in one or both legs, variation of the density of liquid in each leg due to temperature gradients, and leakage from the high pressure to the low pressure leg through any defective bypass valving. To eliminate air or vapors, a vent valve should be provided at the highest point and a drain valve at the lowest point in each leg. Systems need purging prior to calibration and should be checked periodically for presence of air. To minimize effects of possible density gradients in the condensate in each pressure sensing line (exposed to steam temperature at the

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* Trade names are used in this paper as a means of identification. They do not imply endorsement by the National Bureau of Standards.

pressure tap and to room temperature gradients if unlagged), good practice dictates keeping these lines short and close together, nearly horizontal if possible (horizontal pipe run), with the lines sloping slightly downward toward the transmitter. With high range transmitters such as 100 in. H_2O, this density gradient effect should be neglible, but when attempting to measure a few tenths of an inch of water, this effect may be significant though essentially "unknowable". The bypass valving for the transmitter should provide a positive check on bypass leakage. Figures 1 and 2 show a schematic diagram and view of one metering installation using two differential pressure transmitters. Thus, installation using good practice techniques is essential and measurements should be confined to high ΔP whenever possible.

3. Metering System Calibration. As mentioned, for the most accurate measurements, the metering system including adjacent inlet and exit piping along with its flow straightener and the differential pressure measuring equipment should be calibrated directly at a calibration facility with the same fluid (steam) at the same temperatures, pressures, and flow range as those existing during application. An alternate would be use of a suitable transfer reference flowmeter calibrated directly on steam and then installed on line at the application site. Since these approaches are usually expensive, time consuming, and often not practical, (lack of available calibration facilities, or existing building systems piping unsuitable), other approaches to the calibration problem must be considered. One possibility is the direct calibration of the metering system using a liquid such as water over the Reynolds number range of interest (thereby obtaining the coefficient of discharge for the orifice directly) along with the use of published fluid expansion factors for steam [1] for calculation of the flowrate. Another possibility, and the one used in this energy study, is direct calibration of just the differential pressure and the steam temperature and pressure measuring systems, and use of known orifice meter coefficients and fluid expansion factors [1]

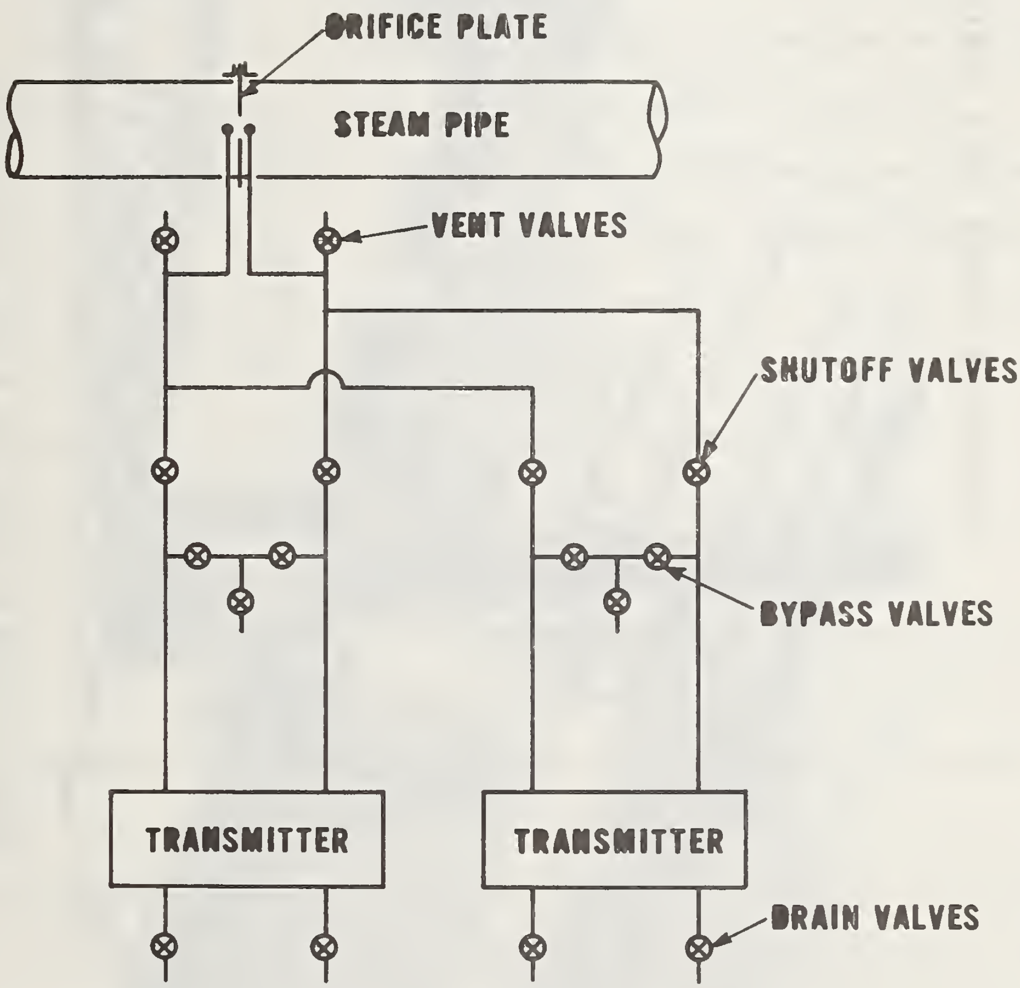

Figure 1. Orifice meter installation using two pressure transmitters, one high, one low, and showing shutoff, vent, drain, and bypass valves

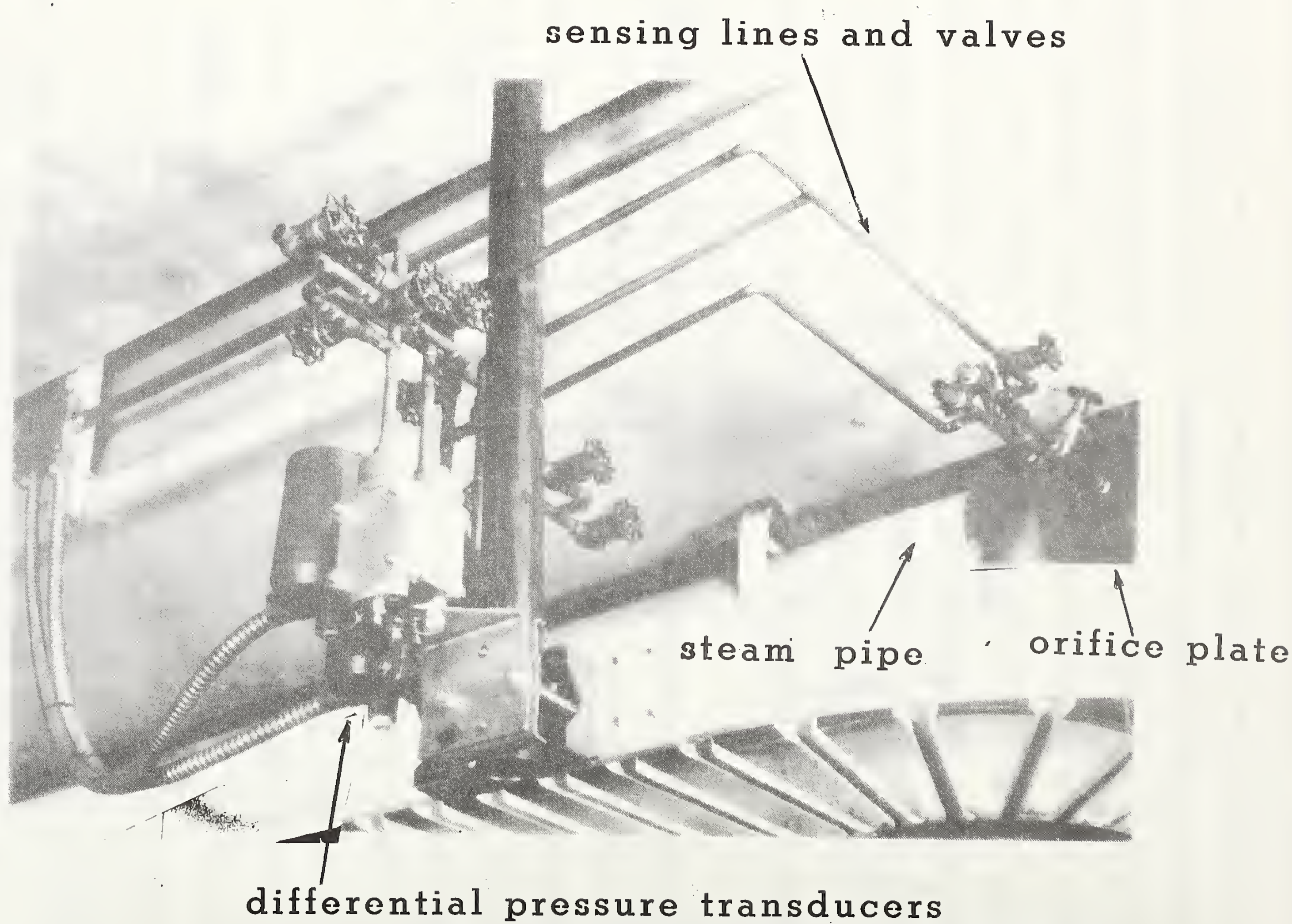

Figure 2. A typical steam metering installation

in determining the flowrate.

Calibration of the ΔP system should be conducted on site if possible. The calibration equipment may range in complexity from liquid manometers (vertical, inclined, or micro type using water or mercury) to laboratory reference type pressure transducer equipment incorporating a digital readout and automated computational features. Results given here were obtained with vertical manometers using water or mercury. In any event, the importance of calibration on site and the establishment of an ongoing calibration program should be emphasized. This program should include establishing a definite calibration procedure, and performing calibrations on a periodic basis to monitor the performance of the differential pressure systems. Use of the control chart method, giving transmitter system performance accumulated periodically is recommended. Several points between zero and full scale ΔP should be checked. If building system flow can be stopped momentarily, the calibration procedure should include a no flow (zero) ΔP check.

To summarize, certain design considerations, namely the flowmeter installation, the differential pressure measurement, and the metering system calibration have been briefly discussed with reference to systems installed in the current NBS program. It is felt these are basic topics of interest to others involved in similar building system energy monitoring programs. Next, a method is presented for estimating the uncertainty of energy usage for the case here, where the flowmeter primary element (orifice) receives no direct calibration, but only the meter differential pressure, and the steam pressure and temperature instrumentation are calibrated directly.

III. ESTIMATE OF UNCERTAINTY

A statement of the amount of energy used based on site measurements may be viewed as incomplete unless it includes an assessment of measurement uncertainty. In many conservation matters, the level of "threshold" savings will depend on this uncertainty.

Several introductory statements are needed at this point. The uncertainty or (in)accuracy is usually considered to include two types of error*: systematic error and random error. Systematic error introduces bias which cause the measured value of a quantity under specified conditions to be consistently either too high or too low with respect to the true value. Random or precision error pertains to those errors which, when repeated measurements are taken of the same quantity under specified conditions, result in a scatter about the average of these measurements. In making measurements where the true value of a quantity is unknown, for example the flowrate in a pipe, observations from two independent measuring systems connected in series can be used as a means of estimating the uncertainty. That is, the presence of systematic error can be detected and under certain conditions, the random error in each system can be estimated. This is essentially the case when calibrating a flowmeter directly with separate calibration equipment (calibrator) where the calibrator performance becomes arbitrarily the true value. Differences between the average values of the calibrator and the flowmeter performances are then assigned to the flowmeter as a systematic error (correction factor, calibration factor) and from the scatter of these measurements, a random error for the flowmeter such as the standard deviation may be estimated. A random error and a possible systematic error associated with the calibrator itself may be accounted for separately, but most often these errors are included in the errors assigned to the instrument being calibrated.

* Error is defined as the difference between the value indicated by a measurement process and the true value.

However, the use of independent systems for routine on line measurements, although most basic and sound, is not usually used in building technology work simply because successful design, installation, debugging and operation of just one measurement system is often task enough. Rather, a single measurement system is used and, when required, the uncertainty estimate is usually based on results of direct calibration of system components, or on an analysis of effects of different parameters on their performance using error analysis, or a combination of both.

In this section, the uncertainty in the energy usage through steam consumption in the Materials Research Building at NBS is considered in detail, and an illustrative calculation of the uncertainty in the steam consumed over a period of one year is given. In brief, this consists of determining the systematic error and the random error for the energy usage, both of which will be found to be flowrate dependent. Since the steam flowrate varies with time (hourly, daily, seasonly), the systematic error is "weighted" with time to determine an effective overall uncertainty for the one year period. For a large number of data, as would be collected over a period such as a year, the effects of random error essentially disappear. For a single observation, the uncertainty would be expressed in a statement which includes both the systematic error and the random error.

1. Systematic Errors. These errors, due to bias in the measurement procedure, are usually composed of both "known" and "unknown" components. A known systematic error is defined as one in which the magnitude and sign are known for any given set of operating conditions. Such errors are removed by correction factors, and henceforth in this report, this type of error will be termed correction factor. In the steam flowrate measurements here, correction factors were used to remove bias due to:

- the variation of the orifice discharge coefficient C with Reynolds number

- the variation of fluid expansion factor Y with parameter $\Delta P/P\gamma$

- the variation of steam density ρ with P and T, and

- the orifice area expansion (parameter F_a) with T.

An unknown systematic error is defined as one in which the magnitude and sign are unknown, but the bounds in which the error will likely remain is known or can be estimated. Here henceforth in this report, this type of error will be termed systematic error. These errors include:

- the deviation from a linear response of the differential pressure transmitter

- the zero and span shift due to ambient temperature changes for this instrument

- the estimated error in the calibration procedure for this instrument

- the uncertainty or tolerance in the discharge coefficient C as assigned by the ASME [1]

- the tolerance in the expansion factor Y assigned by the ASME [1], and

- the uncertainty in orifice diameter d and pipe diameter D due to manufacturing tolerances, in lieu of direct measurements of these quantities for each installation.

The bounds for the transmitter errors are based on ratings as published by the manufacturer. On this basis then, the purpose of the current calibration program is to check and monitor transmitter performance against the manufacturer specifications. However, these transmitter errors could be reduced significantly or essentially eliminated through an extensive calibration program in which the performance curve (correction factor) is established and monitored for each transmitter, provided each transmitter operates in a constant or known ambient temperature environment. Such may require individual temperature-controlled housings, and all of this may be impractical unless maximum accuracy

is required. Zero and span shifts due to line pressure were found negligible for the transmitters used. Zero and span shifts due to ambient temperature are independent effects according to the manufacturer. Errors due to tolerances on C and Y could be reduced significantly by direct calibration of the orifice meter systems flowing steam at operating conditions P and T.

When considering a system having several sources of systematic error, a decision has to be made as to how these errors will be combined. When there are many independent sources of error, each having equal effect on the error of the result, linear addition of the errors may result in an overall systematic error too pessimistic (too large), and one researcher [3] states "if five or more of the largest independent error sources have approximately equal effects on the error in the result, i. e., if the values of each error are of about the same magnitude, the laws of chance could reasonably be expected to apply." This means some errors are expected to be positive, and some negative. Thus, the two types cancel each other to some extent, and combination of the errors on an RSS (root-sum-square) basis can be justified. On the other hand, when there are just two independent sources of error, combination should be on a linear basis [6]. In some cases the method of combination then may become controversial and arguments may even arise on the use of linear addition in combining the individual systematic errors; that such an approach is too conservative or pessimistic. A counter argument is that while use of the individual error approach may be the only practical method for a given program, it does suffer from the possibility of omitting unknown (but important) sources of error. The use of linear addition, therefore, tends to counteract these possible omissions.

In this analysis on the measurement of steam flowrates, the largest error is nominally about twice the next largest error for each meter*, and even though there are 4 to 6 independent error sources for each meter, the smallest error being about 1/10th the largest error, qualification for combining errors on an RSS basis as set forth in the criterion above [3] would be weak. Further, when combining systematic errors from the two meters, there is only a 50/50 chance that the errors tend to cancel, i.e., when the error of one meter is "+", there is equal chance the other may be "+", or "-". Therefore, for these reasons, the (likely bounds to the) overall systematic error will be obtained by linear addition of the individual error sources.

2. Random Errors. Due to the nature of this type error and from propagation of error theory, for example [4], random errors can be combined on an RSS basis. In this analysis, the random errors included are:

- the differential pressure transmitter hysteresis (repeatability)
- the effects of variation of P and T on steam enthalpy h (through ρ)
- an allowance for variation in density of the condensate in the transmitter pressure sensing lines
- the accuracy of the analog/digital (A/D) conversion of the transmitter output, and
- the accuracy of P, T, and T_c measurements.

Tables 1, 2, and 3 list the correction factors, the systematic errors and the random errors as assigned to energy rate E, mass flowrate M, and differential pressure h_w, respectively**. It is noted that effects of variation in steam density ρ include the following: a correction factor $e_{\rho c}$ for the flowrate; (part of) the random error e_h for the enthalpy; and a random error $e_{\dot{\rho}}$ for the flowrate. The effect of variation of ρ with P and T is much greater on the flowrate than on the enthalpy, and since correction

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* Appendix C, Table C1.

** Systematic errors are denoted by an "s" in the subscript and correction factors by a "c".

factors are applied manually at present rather than being computer based, considerable time savings result from applying just one correction factor, i.e., $e_{\rho c}$ on the flowrate. The effect of this simplification on the accuracy of the results is negligible.

Following are the basic energy rate and flowrate equations used in this analysis, and corresponding equations from error propagation theory for evaluation of the systematic and random errors.

3. Basic Relations. As stated previously, the steam supply line entering the Materials Research Building divides into two branches, denoted north (n) and south (s) with an orifice meter installed in each branch. This steam is slightly superheated at pressure P and temperature T, measured immediately upstream of the branch. Condensed steam at temperature T_c returns to the power plant at atmospheric pressure.

The basic relation for net rate of energy consumed is:

$$E = (M_n + M_s)[h - c_p(T_c - 32.0)] \tag{1}$$

The basic relation for mass flowrates M_n and M_s, written as M is, from [1] for example:

$$M = 358.93\ C\ Y\ d^2\ F_a[\rho h_w/(1 - \beta^4)]^{1/2} \tag{2}$$

Applying propagation of error theory to equation 1, the random errors for individual parameters can be combined on an RSS basis giving a random error e_E in the energy rate E such that:

$$\frac{e_E}{E} = \pm \left[\left(\frac{e_{Mn}}{M_n + M_s}\right)^2 + \left(\frac{e_{Ms}}{M_n + M_s}\right)^2 + \left(\frac{e_h}{\Delta h}\right)^2 + \left(\frac{e_{Tc}(-c_p)}{\Delta h}\right)^2\right]^{1/2} \tag{3}$$

TABLE 1

Random Error and Systematic Error Assignments for Energy Rate E

Error Symbol	Description	Random e_E	Systematic e_{Es}
e_M	Flowrate, see table 2	X	
e_h	Variation of enthalpy with density ρ, and accuracy of P & T measurement	X	
e_{Tc}	Variation of condensate temperature and accuracy of Tc measurement	X	
e_{Ms}	Flowrate, see table 2		X

TABLE 2

Random Error, Systematic Error and Correction Factor Assignments for Flowrate M

Error Symbol	Description	Random e_M	Systematic e_{MS}	Correction Factor
e_{Cs}	Tolerance on discharge coefficient C		X	
e_{Ys}	Tolerance on expansion factor Y		X	
e_{ds}	Manufacturing tolerance on orifice diameter d		X	
$e_{\beta s}$	Tolerance on beta ratio d/D		X	
e_{ρ}	Variation of density ρ, and accuracy of P & T measurements	X		
e_{hw}	Differential pressure, see table 3	X		
e_{hws}	Differential pressure, see table 3		X	
e_{Cc}	Variation of C with Reynolds number			X
e_{Yc}	Variation of Y with h_w/P			X
e_{Fc}	Thermal expansion of the orifice			X
$e_{\rho c}$	Variation with density ρ, and P & T			X

TABLE 3

Random Error and Systematic Error Assignments for Differential Pressure ΔP

Error Symbol	Description	Random e_{hw}	Systematic e_{hws}
e_{Ts}	Transducer linearity		X
e_{As}	Transducer ambient temperature zero and span shift, RSS basis		X
e_{th}	Transducer hysteresis	X	
e_{Rs}	Reference calibration transducer current and reference pressure, RSS basis		X
e_{SL}	Density variation in sensing lines, allowance for	X	
$e_{A/D}$	Analog/digital conversion, computer system	X	

The flowrates M_n and M_s refer to the north and south branches, respectively. From simultaneous values of M_n and M_s and corresponding values of e_{Mn}/M_n and e_{Ms}/M_s, error e_E/E can be evaluated. Specific heat c_p is assumed constant, thus no term e_{cp} appears. It is shown in Appendix B that for the existing operating conditions all errors are significant, and that e_{Mn} and e_{Ms} control at the lowest ΔP values for each transmitter.

From propagation of errors through equation 2, random errors e_{Mn}/M_n and e_{Ms}/M_s, written as e_M/M, become:

$$\frac{e_M}{M} = \pm \left[\left(\frac{e_\rho}{2\rho}\right)^2 + \left(\frac{e_{hw}}{2h_w}\right)^2\right]^{1/2} \tag{4}$$

In addition to transmitter errors, differential pressure data include possible errors due to the analog/digital conversion and any differences in density of the fluid (condensate) in (nonhorizontal) pressure sensing lines. These errors are assumed random in nature along with the transmitter hysteresis error, and each is assumed to have equal effect. The random error e_{hw} on an RSS basis is then:

$$e_{hw} = \pm \left[\left(e_{th}\right)^2 + \left(e_{A/D}\right)^2 + \left(e_{SL}\right)^2\right]^{1/2} \tag{5}$$

Thus, random error e_{hw} has 3 components, those due to ΔP transmitter hysteresis e_{th}, analog/digital (A/D) conversion error $e_{A/D}$, and sensing line error e_{SL}. These errors are discussed in detail in Appendix B.

Random errors must be expressed on the same basis, i.e., confidence intervals of the same degree or the same number of standard deviations. For this analysis, the random error data and assumed correspond to two standard deviations or 2σ. On this basis, the estimated random errors are likely not exceeded 95 percent of the time.

The correction factors e_{Cc}, e_{Yc}, $e_{\rho c}$ and e_{Fc} listed in table 2 are applied directly to observed flowrates M_o. The systematic errors, not known explicitly, are estimated in terms of bounds or limits likely not exceeded. No systematic errors in h and c_p were assumed to exist. Thus from propagation of errors through equation 1 and combining on a linear addition basis, the systematic error e_{Es} in energy rate E is:

$$\frac{e_{Es}}{E} = \pm\left[\frac{(e_{Ms,n}/M_n)\ M_n}{M_n + M_s} + \frac{(e_{Ms,s}/M_s)\ M_s}{M_n + M_s}\right] \tag{6}$$

where $e_{Ms,n}$ systematic error in flowrate M_n

$e_{Ms,s}$ systematic error in flowrate M_s.

Table 2 lists the systematic errors for flowrate M, namely e_{Cs}, e_{Ys}, e_{ds}, $e_{\beta s}$ and e_{hws}. From propagation of errors through equation 2 and combining on a linear addition basis as discussed above, the systematic error in flowrate M is:

$$\frac{e_{Ms}}{M} = \pm\left[\frac{e_{Cs}}{C} + \frac{e_{Ys}}{Y} + \frac{2\ e_{ds}}{d} + \frac{e_{hws}}{2\ h_w} + \frac{2\ \beta^3\ e_{\beta s}}{1 - \beta^4}\right] \tag{7}$$

Systematic error e_{hws} has three components, e_{Ts}, e_{As}, and e_{Rs} listed in table 3. They are, respectively, the transmitter linearity characteristic, the effects of ambient temperature on transmitter performance and the estimated accuracy of the calibration process. All are assumed have equal effect on e_{hws} and thus on an linear addition basis:

$$e_{hws} = \pm\left[e_{Ts} + e_{As} + e_{Rs}\right] \tag{8}$$

These errors are discussed in greater detail in Appendix C.

A statement expressing the estimate of the overall uncertainty of the energy rate can be made using the systematic error and the random error, provided each error is identified or reported separately. For a conservative estimate:

$$\text{Maximum Overall Uncertainty} = \pm\ (e_{Es}/E + e_E/E) \tag{9}$$

For perhaps a more probable, realistic estimate:

$$\text{Probable Overall Uncertainty} = \pm\ \left[(e_{Es}/E)^2 + (e_E/E)^2\right]^{1/2} \tag{10}$$

The uncertainties above refer to a single observation. The effects of random error involving many observations are expected to essentially disappear. This is the case when considering uncertainty in energy consumed over a sustained period, such as a few months or a year. The systematic error, however, represents a bias which remains and when it can not be quantified explicitly, it becomes an estimate of the bounds or limits to the error which is likely not exceeded.

The operating conditions for steam supplied to the Materials Research Building are summarized in table 4, and characteristics of the instrumentation systems used to measure this steam are listed in table 5.

4. Error Analysis Results. In this section, results of error analysis are presented for steam consumed with the above operating conditions and instrumentation systems. These results include the correction factors as applied to the steam flowrates, and analysis of the systematic errors and the random errors. Finally, using a set of typical building steam consumption data, an estimate of the effective overall uncertainty for energy consumed over a one year period is given. The uncertainty is found due primarily to the errors encountered in the differential pressure measurement and the tolerance or uncertainty in the orifice discharge coefficient.

4.1 Correction Factors. Figures 3 and 4 give correction factor M/M_o for the flow range 160 to 3200 lb/hr, where M_o is the observed or indicated flowrate output from the computer for either flowmeter. These data include correctious for errors e_{Cc} due to variation in the orifice discharge coefficient, e_{Yc} due to variation in the steam expansion factor, e_{Fc} due to thermal expansion of the orifice, and $e_{\rho c}$ due to steam density variation. Detailed explanation of these corrections are given in Appendix A. Thus, mass flowrate becomes

$$M_n = (M/M_o)M_{o,n} \quad \text{and} \quad M_s = (M/M_o)M_{o,s} \tag{11}$$

For the operating conditions given, M/M_o varies through a range of about 8 percent. For maximum utility, steam data $\rho = \rho(P,T)$ and corrections e_{Cc} and e_{Yc} should be computer based.

4.2 Random Error Analysis. Figure 5 shows results of random error calculations of e_M/M (e_{Mn}/M_n, e_{Ms}/M_s) using equation 4. This error is flowrate dependent through the term $e_{hw}/2h_w$ where h_w varies as M^2 and its minimum value depends on e_ρ. Error e_{hw} includes effects of errors e_{th}, $e_{A/D}$ and e_{SL} as listed in table 3. Error e_ρ is due to uncertainty in measurements of steam conditions P and T. Appendix B gives details of these calculations.

By using two ΔP transmitters, denoted HIGH and LOW, the random error is confined to a range 0.5 to 2.7 percent of flowrate for the nominal range 160 to 3200 lb/hr, with smallest error at highest flowrates for each meter. The improvement in precision by the use of two transmitters is quite evident. As shown, use of the HIGH transmitter alone over this flow range would result in random error as high as about 30 percent at the lowest flowrate.

The random error e_E/E in the energy rate expressed in equation 3 depends on e_{Mn}, e_{Ms}, e_h and e_{Tc}. All are significant with the e_M values controlling at the low end of the ΔP range of each transmitter. As discussed in Appendix B, e_E/E will vary upward from about 0.7 to 2 percent for the system presented here.

TABLE 4

Operating Conditions for Steam Supplied to Materials Research Building

Temperature T = 290°F, nominal; data collected indicated annual variation in the range 280 to 299°F

Pressure P = 27.3 psia, nominal; with annual variation in the range 26.8 to 27.9 psia

Enthalpy h = 1185.0 Btu/lb, nominal; range 1179.8 to 1190.0 Btu/lb

Condensate temperature T_c = 176°F nominal; with annual variation in the range 173 to 179°F

Net enthalpy Δh = 1041.0 Btu/lb

Steam flowrates M_n and M_s, each range 400 to 2900 lb/hr

TABLE 5

Instrumentation Systems for Steam Measurement

Flowmeters, one each branch (north, south)

Pipe Size D = 6.057 inches

Orifice plate, square edge, stainless steel

$d = 2.359$ inches

$\beta = 0.389$

Corner pressure taps

Differential pressure transmitters, manufacturer specifications, one HIGH ΔP, one LOW ΔP transmitter for each meter, sensing lines connections. see figure 1.

Item	HIGH ΔP	LOW ΔP
Full Scale	105	40 in. H_2O
Adjusted Span (h_{wsp})	105	8 in. H_2O
Linearity error (e_{Ts})	0.35%	0.35% span
Ambient temperature effect, zero and span shift error (e_{As})	1.40%/100°F	1.75%/100°F span
Hysteresis error (e_{th})	0.10%	0.10% span

Steam Temperature Transmitter, resistance type, 40K ohms at 77°F, well immersion, range 250-475°F, system accuracy ± 1.5°F (e_T)

Steam Pressure Transmitter, pressure-to-potentiometer, resistance type, range 0 to 30 psig, system accuracy ± 0.25 psi (e_p)

Condensate Temperature Transmitter, resistance type, 40K ohms at 77°F, well immersion, range 250-475°F, system accuracy ± 1.5°F (e_{Tc})

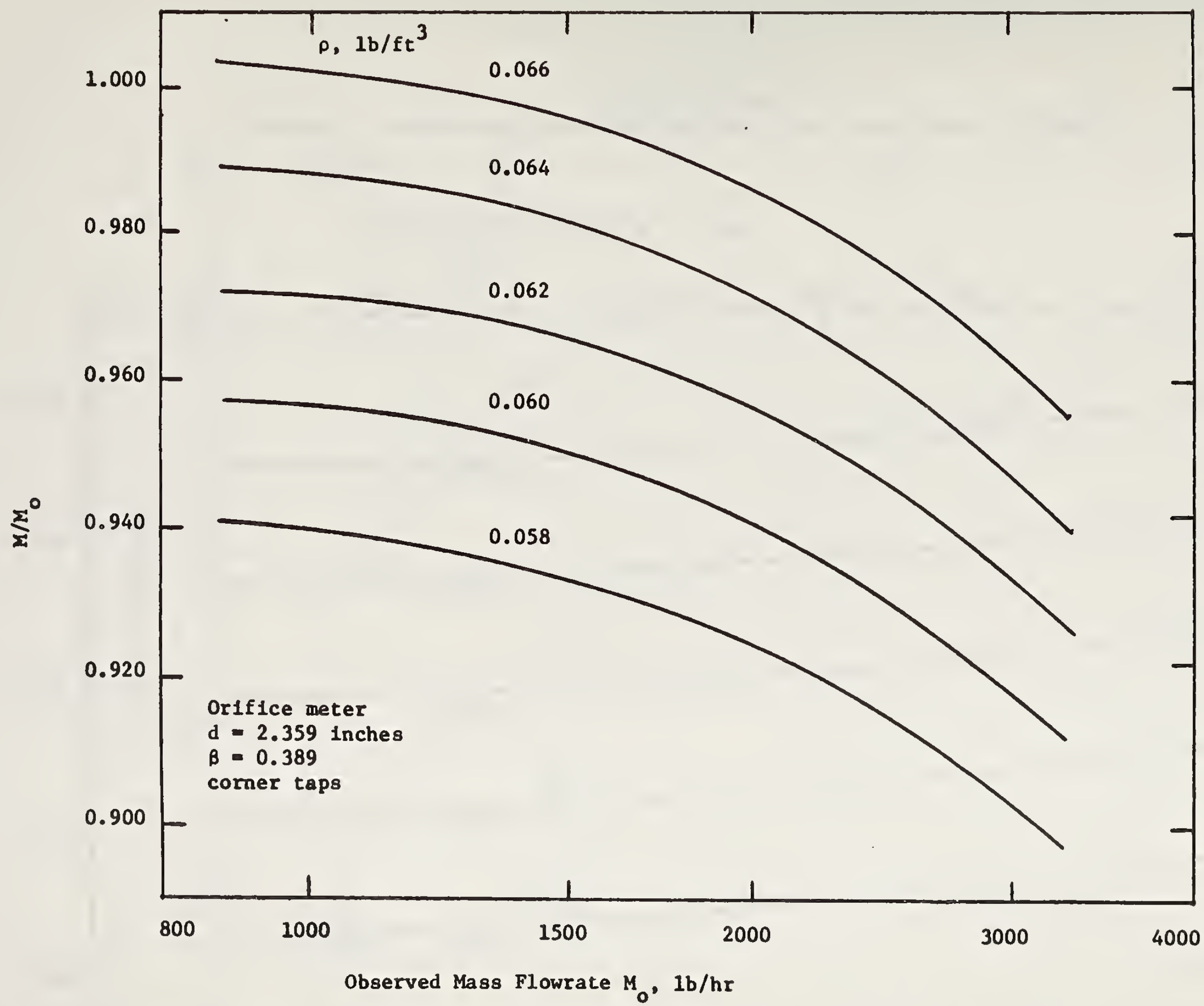

Figure 3. Correction factors M/M_o for north and south branch flowmeters, 900 to 3200 lb/hr

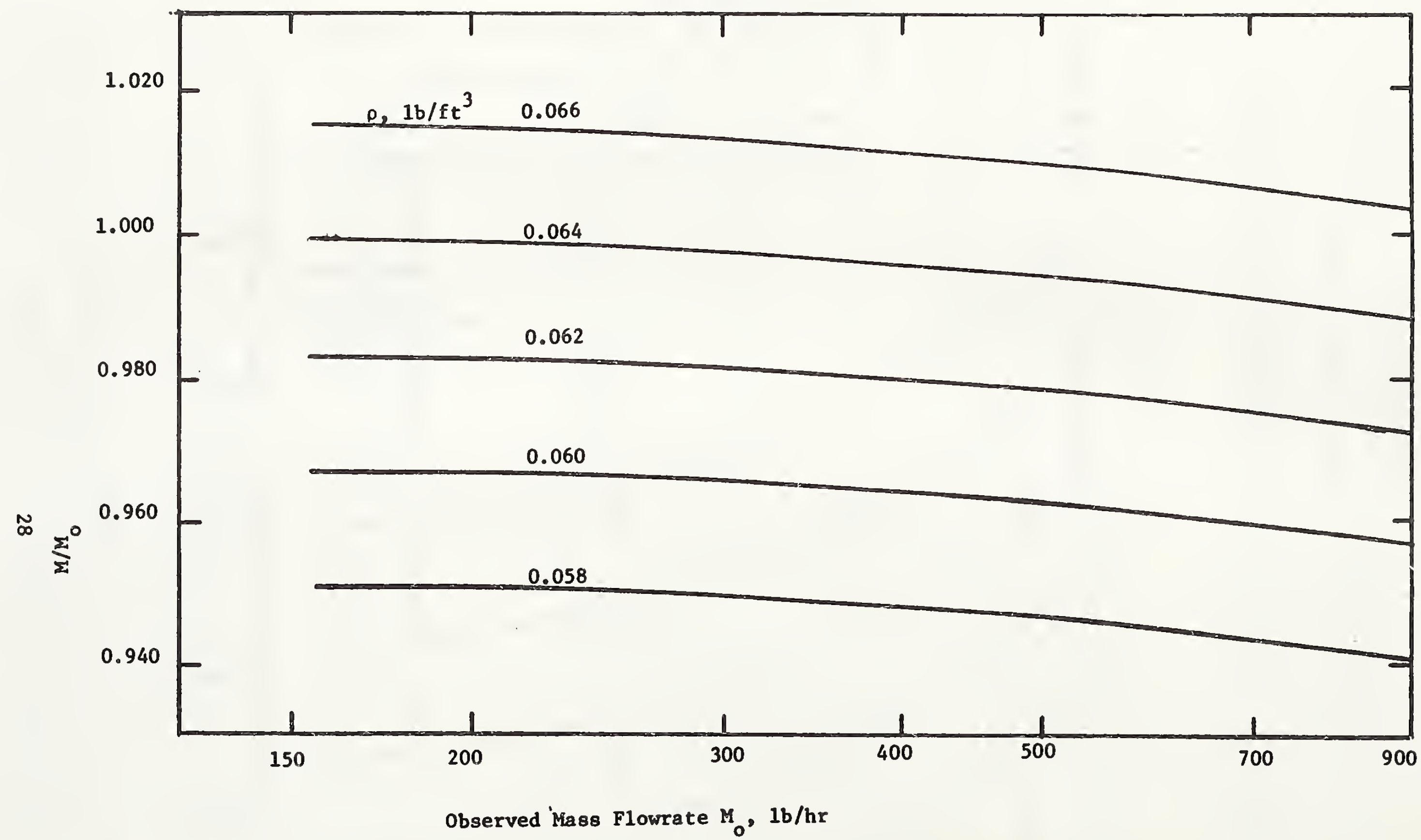

Figure 4. Correction factor M/M_o for north and south branch flowmeters, 160 to 900 lb/hr

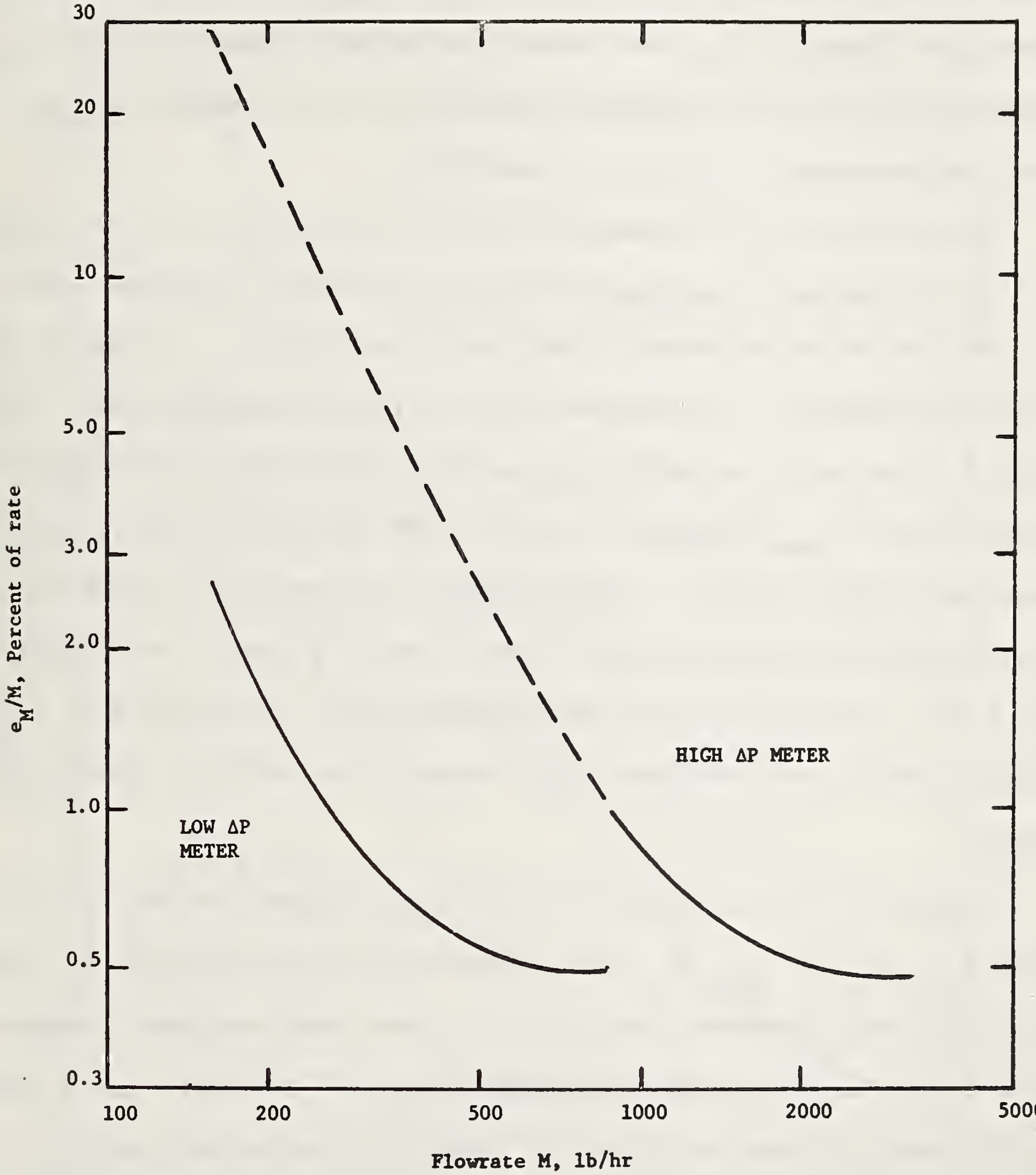

Figure 5. Random error in flowrates M_n and M_s

4.3 Systematic Error Analysis. Figure 6 shows systematic error in the flowrate e_{Ms}/M ($e_{Ms,n}/M_n$, $e_{Ms,s}/M_s$) calculated through equation 7. This error is primarily due to the tolerance in the orifice discharge coefficient and the error in the differential pressure h_w. The components of e_{hws} are the differential pressure transmitter linearity e_{Ts}, the transmitter ambient temperature error e_{As} and the estimated error in the calibration procedure for the transmitter, e_{Rs}. These errors are discussed in detail in Appendix C.

Flowrate error e_{Ms}/M ranges from about 1.6 percent of rate to 36 percent for HIGH and LOW meter configuration over the nominal flow range 160 to 3200 lb/hr, with smallest error at highest flowrates for each meter. At high ΔP values for each transmitter, the tolerance in the orifice discharge coefficient (e_{Cs} = 1.00 percent) and error e_{hws} are both significant, while at low ΔP values error e_{hws} dominates. For the HIGH transmitter alone, e_{Ms}/M ranges very high at low ΔP. This emphasizes the reason for using more than one transmitter when flow will vary through a range of more than, say, 3 to 1. This system with two transmitters is considered weak for extended use at very low flows, e.g., range 160 to 400 lb/hr where $E_Ms/M > 6.0$ percent.

Systematic error in the energy rate e_{Es}/E depends entirely on flowrate errors $e_{Ms,s}/M_s$ and $e_{Ms,n}/M_n$ and is calculated through equation 6. Errors in enthalpy e_h and condensate temperature e_{Tc} have been assigned as random errors, and the specific heat of the condensate is assumed constant. Since error e_{Es}/E depends on flowrates M_s and M_n, this error varies with building operating conditions as these flows vary independently with loads. Thus, no single value e_{Es}/E applies. However, an effective or weighted systematic error can be obtained by analyzing steam flowrate usage data over an extended building operating period. An illustrative calculation is given in the next section.

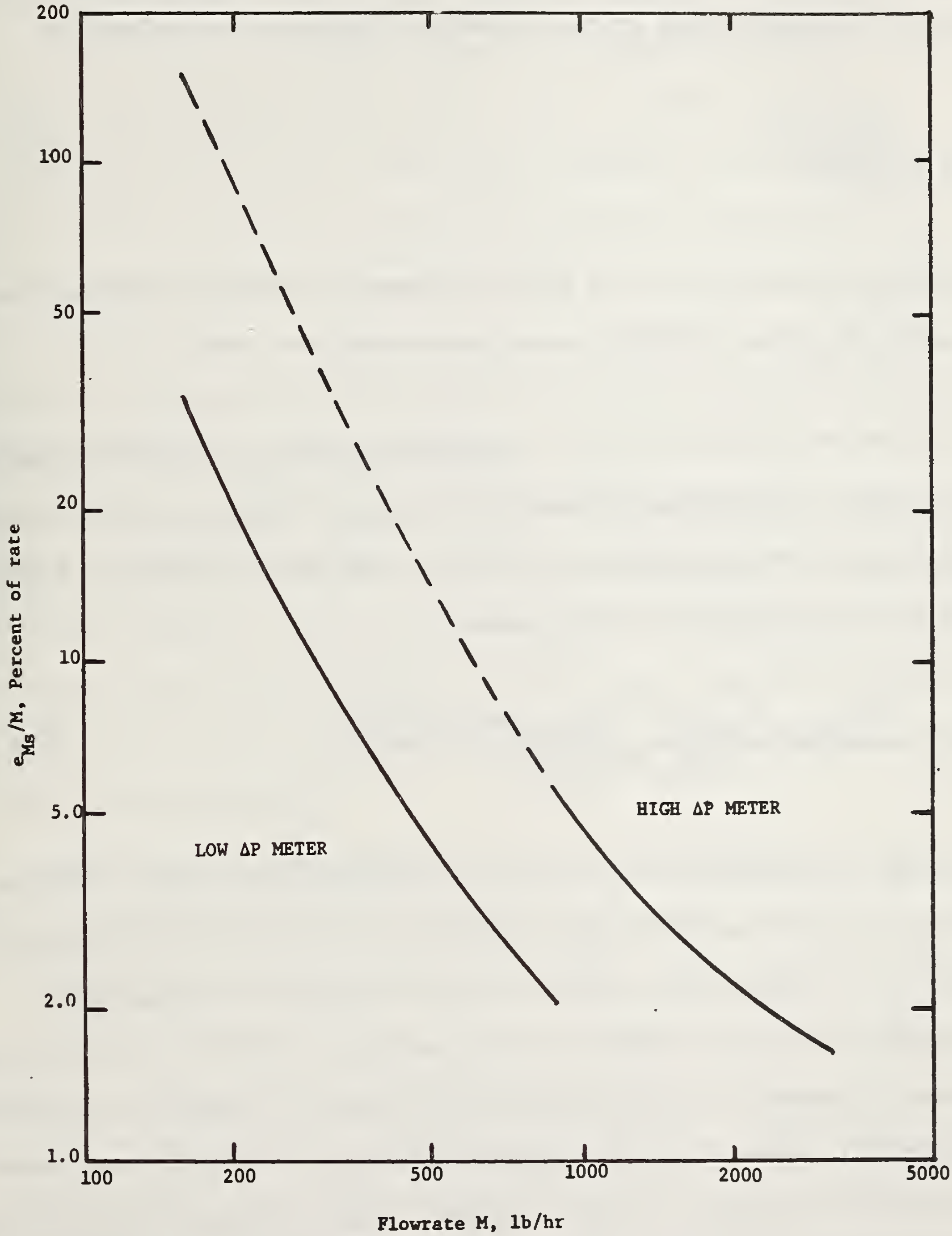

Figure 6. Systematic error in flowrates M_n and M_s .

5. Uncertainty in Energy Usage. The uncertainty in energy usage for a period of one year has been determined from the systematic error in the energy rates. Effects of random errors become negligible with such a large number of observations. Therefore, the uncertainty A_s for accumulated usage can be written as:

$$A_s = \frac{\sum_i e_{Esi} \Delta t_i}{\sum_i E_i \Delta t_i} \tag{12}$$

where $\sum_i e_{ESi} \Delta t_i$ denotes the sum of the systematic errors accumulated over a year and, $\sum_i E_i \Delta t_i$ is the total steam energy used in a year.

With random variations in Δh, accumulated error A_s is dependent only on flowrate M and corresponding systematic error e_{Ms}. With e_{Ms} in terms of e_{Ms}/M (figure 6) and when Δt_i applies to both north and south flowmeters, equation 12 applied to the two-branch circuit becomes:

$$A_s = \frac{\Sigma \left[(e_{Msi,n}/M_{ni}) M_{ni} + (e_{Msi,s}/M_{si}) M_{si} \right] \Delta t_i}{\Sigma \ (M_{ni} + M_{si}) \Delta t_i} \tag{13}$$

Energy consumption data from actual operation, such as data collected from energy monitoring and control systems, may be used for the uncertainty calculations. Calculation details for a set of typical building steam consumption data using equation 13 are presented in table 6. In this case, the steam consumption of the building was estimated by using the temperature bin method [7]. Then, the whole year was divided into eight steam flowrate bins according to the magnitude of the flowrates. These estimated operating data are given in terms of steam rates M_n and M_s for time intervals Δt_i, the accumulated time corresponding to the listed flowrates (columns B, C and E). Also listed for equation 13 are values of the numerator (column G) and the

denominator (column H) quantities for each Δt_i, and accumulated sums which apply to the transmitter system used. Error data, columns D and F are from figure 6. Thus, for the HIGH and LOW meter configuration, the uncertainty in the energy consumed for the 1 year period is estimated not to exceed 3.2 percent. With a net enthalpy change Δh of 1041 Btu/lb (table 4), the total energy consumed was $1041(21.54 \times 10^6) = 22.423 \times 10^9$ Btu where 21.54×10^6 is the total pounds steam consumed for the 1 year period. A statement which includes the uncertainty could then be made such as: "The steam consumed during the one-year period . . . . . . was $(22.423 \pm 0.718) \times 10^9$ Btu, where the uncertainty due to systematic error in the measurements is estimated not to exceed 0.718×10^9 Btu and the net effect of random errors are assumed negligible."

For the single transmitter case using the HIGH meter, the estimated uncertainty is 4.3 percent. While for this set of building data, the improvement from the two transmitter case is just 1.1 percent, it is noted the LOW transmitter was is use only about 1/4 of the time. In any event, these data illustrate the dependence of the uncertainty on both the operating conditions and the measurement systems characteristics.

In particular, the characteristics of the flow measurement system are most important, where with differential pressure type systems, the ΔP transmitter will inevitably be a "crucial link" in the system. When operating conditions show that flowrates vary but little, then one transmitter should suffice, sized full scale at or slightly above the operating flowrate. When operating conditions vary through a large range as in this example, or where a low flowrate occurs for a large portion of the total operating time, then the two transmitter system appears feasible. An added advantage to the two transmitter system is that of system self-checking, i. e. comparison of system LOW and HIGH outputs whenever ΔP (h_w) is in the overlap region. Whenever the two outputs differ by more than a predetermined amount, an alarm or diagnostic is output and appropriate action taken. The present NBS software system includes this feature.

TABLE 6

Uncertainty in Accumulated Energy Usage

	i	Δt_i	M_{ni}	$\frac{e_{Msi,n}}{M_n}$	M_{si}	$\frac{e_{Msi,s}}{M_s}$	$(D \cdot C + F \cdot E)B$ $\times 10^{-3}$	$(C + E)B$ $\times 10^{-3}$
		hrs	lb/hr	%	lb/hr	%	lb·%	lb
col.	A	B	C	D	E	F	G	H

HIGH and LOW Transmitters

	i	B	C	D	E	F	G	H
	1	1139	449	5.25	438	5.50	5429	1010
	2	350	449	5.25	588	3.45	1535	363
	3	526	711	2.75	588	3.45	2096	683
	4	350	1252	3.65	588	3.45	2309	644
	5	5169	1252	3.65	1369	3.25	46619	13548
	6	613	1881	2.28	1855	2.32	5267	2290
	7	438	2266	1.95	2312	1.93	3890	2005
	8	175	2868	1.72	2830	1.73	1720	997
Sum		8760					68865	21540

Uncertainty $A_s = \Sigma G / \Sigma H = 68865/21540 = 3.2\%$

HIGH Transmitter

	i	B	C	D	E	F	G	H
	1	1139	449	18.8	438	19.9	19542	1010
	2	350	449	18.8	588	10.1	6695	363
	3	526	711	8.1	588	10.1	6153	683
	4	350	1252	3.65	588	10.1	3678	644
	5	5169	1252	3.65	1369	3.25	46619	13548
	6	613	1881	2.28	1855	2.32	5267	2290
	7	438	2266	1.95	2312	1.93	3890	2005
	8	175	2868	1.72	2830	1.73	1720	997
Sum		8760					93564	21540

Uncertainty $A_s = 93564/21540 = 4.3\%$

The question can be raised concerning practical ways to improve the uncertainty. The first priority item would be the reduction of the systematic error due to the pressure transmitter systems. Such would require periodic calibration of the transmitters resulting in a linearity error "curve" as a function of ΔP, or the equivalent, for each transmitter. Such data would then be applied as a correction factor for h_w. In addition, adequate control of transmitter ambient temperature environment would be needed. Also, it would be necessary to demonstrate that each transmitter is not significantly influenced by other parameters such as line pressure level and that hysteresis (repeatability) is truly a random characteristic. Assuming such a program results in a systematic error e_{hws}/h_w of 0.50 percent or less, (now considered a tolerance) then error e_{Ms}/M from equation 7 would not exceed 1.5 percent, where $e_{hws}/2h_w$ = 0.25 percent, e_{Cs}/C = 1.00 percent, e_{Ys}/Y = 0.25 percent, and e_{ds} and $e_{\beta s}$ have been accounted for. With $e_{Ms}/M \leq 1.5$ percent, then from equations 6 and 13, the uncertainty in the accumulated energy $A_s \leq 1.5$ percent.

The second priority item concerns the present tolerances: orifice discharge coefficient e_{Cs} and fluid expansion factor e_{Ys}. These tolerances could be reduced significantly by direct calibration of the orifice meter system on steam at line conditions P and T. In this case, e_{Ys} approaches zero and e_{Cs} becomes dependent on the performance of the calibrator facility. Allowing 0.5 percent for the uncertainty in the calibrator performance, the uncertainties e_{Ms}/M and A_s then might be reduced by a factor of two, to, say, 0.75 percent. Alternately, the orifice meter could be calibrated on a liquid such as water. The tolerance e_{Ys} = 0.25 percent would still be needed, and allowing 0.25 percent for the uncertainty in the liquid calibrator performance, the uncertainties e_{Ms}/M and A_s could be reduced significantly, to, say, 0.75 percent. While these estimates include some speculation, it is true that extending the calibration program will improve system performance most at low energy rates and least at the higher rates.

The requirements of individual programs would dictate whether the first or both of the two items above would be practical or not. It will only be noted here that where calibration facilities flowing steam are unavailable, there appears not much choice other than use of (uncalibrated) meters such as the orifice, venturi or flow nozzle because the flow characteristics of these are considered known when the installation conditions are met. Also, the use of suitable condensate meters is appropriate should the application allow this. Where a suitable calibrator facility flowing steam is available, other type flowmeters such as the more recently developed vortex shedder type should be considered. The big advantage is that its output, an electrical pulse whose frequency varies directly with volume flowrate, is relatively easy to measure. However, for best accuracy the vortex meter must be calibrated directly on a calibrator flowing steam.

6. Computer Based Calculations. In the foregoing, the uncertainty was noted to be dependent on both building operating conditions and performance of the measuring systems. Because of this, the estimate of uncertainty involves handling a number of variables and large amounts of data. Its calculation becomes lengthy and complex compared to the basic calculations of flowrate and energy flow. Therefore, it is concluded that when such estimates are needed on a routine basis, they should best be computer based. The following considers calculations pertaining to the previous example for use with a computer based system where the correction factors (e_{Cc}, e_{Yc}, e_{Fc} and $e_{\rho c}$) are applied and the uncertainty calculations of the energy measurement are made through software. Assume equations 1 and 2 or the equivalent are being calculated and that computer based measurements of h_w, P, T and T_c are being made. Also, where two transmitters are used for h_w, one HIGH and one LOW, it is advisable that check comparison measurements of h_w are made on line in the overlap region. Calculate in the following priority:

A. Steam density ρ, under program control from current measurements of P and T, for use in equations 1 and 2. This involves storing data in tabular form for $\rho = \rho(P,T)$ for the range of interest and use of linear interpolation, or use of an appropriate equation to calculate ρ directly. Note a check on apparent steam condition could be made. For example, for current P, test for $T > T_s$, where T_s is the saturation temperature corresponding to P. A diagnostic should be output to indicate steam in the saturation or wet condition.

B. Steam expansion factor Y, under program control from current measurements of h_w and P, for use in equation 2. This involves storing data in tabular form for $Y = Y\ (\Delta P/P\gamma)$ for the range of interest of $\Delta P/P\gamma$ and use of interpolation, or calculating Y from an appropriate equation as given, for example, in [1].

C. Orifice coefficient of discharge C, under computer control, for use in equation 2. This involves a calculation of a Reynolds Number (Re), storage of data for each orifice meter in tabular form for C = C(Re) and use of interpolation to determine C. Alternately, an appropriate equation C = C(Re) may be used. Since Re varies with M, a preliminary calculation of M through equation 2 using a nominal value of C will be necessary. In turbulent flow, C normally varies slowly with Re, so that one preliminary calculation of Re will usually suffice. Otherwise, iterative techniques should be used.

With C, Y and ρ determined, calculate current values of flowrate M and energy rate E, and store and output as appropriate for the instrumentation calibration program and calculation of the uncertainty.

D. Read and store under program control all periodic calibration data for h_w, P, T and T_c working instrumentation and manually operated reference calibration instrumentation. This requires (manual) input and processing capability for the reference calibration data. Thus, records of calibration results and checks of instrument performance would be computer based.

E. Calculation of uncertainty in accumulated energy usage A_s for a predetermined period of time using equations 12 or 13 or equivalent. This requires (for equation 13), storage of all flowrates M_i, corresponding Δt_i and calculation of e_{Msi}. The period of time $\Sigma\Delta t_i$ should include sufficient observations so that random error effects approach zero. Alternately, a current value of A_s could be calculated, starting at a designated time, by updating equation 13 at each current M_i observation. This would eliminate storage of M_i data.

F. Calculation of overall uncertainty on a single observation basis, expressing in the form of equation 9 or 10. This requires calculation of e_{Es} and e_E.

IV. PROCEDURE SUMMARY

The following summarizes a suggested procedure for estimating the uncertainty or (in)accuracy in the energy measurements for similar cases flowing steam or other compressible fluids where only the ΔP, P and T instrumentation can receive direct calibration.

1. The system design, installation and usage should conform to good metering techniques. This includes: metering runs which have adequate lengths of straight pipe and use of flow straighteners; ΔP sensing lines horizontal and short with low slopes and no air traps, adequate and convenient provisions for venting and draining, and positive isolation between the high and low pressure legs; and periodic calibrations of the ΔP, P and T systems.

2. Specify sources of possible error. Classify as correction factors, systematic, or random (precision) errors. Systematic errors are those non-random errors of unknown sign and magnitude and for which only the bounds or limits are known or can be estimated.

3. Decide which correction factors will be significant and quantify these. For manual corrections, data such as those of figures 3 and 4 can be calculated. For computer based corrections, software performing calculations such as outlined in Section III 6, A, B and C above can be developed.

4. Calculate bounds for the systematic error in the energy rate, once the method of combining individual errors has been decided. Express error as function of flowrate, as in figure 6. Such data can then be used for estimates of the uncertainty for accumulated energy usage through applications of equation 12 or equivalent, either through manual or computer based calculations as outlined in Section III 6, E.

5. Calculate random error in the energy rate, combining individual errors on an RSS basis. Express error as function of flowrate, as in figure 5. These data are used in any statement of uncertainty as given in equations 9 and 10 for single observations of the energy rate.

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APPENDIX A

CORRECTION FACTOR M/M_o

Actual steam flowrate M is obtained through correction of observed steam flowrate M_o by the computer from the equation:

$$M = (M/M_o)M_o \tag{11}$$

M/M_o is a correction factor which removes bias due to:

- the variation in the orifice discharge coefficient C with Reynolds Number (e_{Cc})
- the variation of fluid expansion factor Y with parameter $\Delta P/P\gamma$ (e_{Yc})
- the variation of steam density ρ with P and T ($e_{\rho c}$), and
- the orifice expansion with T (e_{Fc}).

This correction factor M/M_o was obtained as follows:

1. The observed flowrate measured by the computer is

$$M_o = K(A/999)^{1/2} = K(h_w/h_{wsp})^{1/2}, \text{ where}$$

K	scaling constant, differential pressure transmitter
h_{wsp}	span, ΔP transmitter
A	observed count, A/D coverter output, and
999	full scale count, A/D converter

For the HIGH transmitter, K = 3200 lb/hr and h_{wsp} = 105 in. H_2O, and for the LOW transmitter, K = 883.3 lb/hr and h_{wsp} = 8.00 in. H_2O. Thus

$$M_o = 3200(h_w/105)^{1/2}, \qquad 8.00 \leq h_w \leq 105 \text{ in. } H_2O, \text{ and}$$

$$M_o = 883.3(h_w/8.00)^{1/2}, \qquad 0.26 \leq h_w \leq 8.00 \text{ in. } H_2O$$

For both meters:

$$M_o = 312.29\ (h_w)^{1/2} \tag{A1}$$

The A/D converter was assumed linear with a random error of $\pm$ 1 count, expressed as $e_{A/D}$.

Since $M = 358.93\ CYd^2Fa\ (\rho h_w)^{1/2}/(1-\beta^4)^{1/2}$, (equation 2), a correction factor M/Mo can be expressed as

$$M/M_o = \frac{358.93\ C\ Y\ (2.359)^2(1.004)(\rho)^{1/2}/0.9885}{312.29}, \text{ or}$$

$$M/Mo = 6.4963\ C\ Y\ (\rho)^{1/2}, \text{ where} \tag{A2}$$

$d = 2.359$ inches

$Fa = 1.004$, and

$\beta = 0.389$

The discharge coefficient C is based on data for corner taps given in [2] wherein $C = F_c K_1 (1 - \beta^4)^{1/2}$; $K_1 = 0.6098$ for $\beta = 0.389$ (page 144) and F_c is a function of pipe Reynolds Number R_D as given in Figures B2317, B2318 (page 239). Pipe Reynolds Number is $48M_o/3600\pi D\mu$, where μ is the absolute viscosity of steam at nominal P and T (9.5×10^{-6} lb/ft·s at 27 psia and 290°F). Effects of variation of ρ and μ within the operating range on C (thru R_D) were less than 0.1 percent and were neglected.

The expansion factor is calculated from [1], wherein $Y = 1 - (0.41 + 0.35\ \beta^4)(\Delta P/P\gamma)$, equation II-III-7 (page 208), and where $P = 27.0$ psia, $\Delta P = (0.361)h_w$ psi, and $\gamma = 1.3$, the specific heat ratio for steam. Effects of variation of P within in the operating range on Y were less than 0.2 percent and were neglected.

The orifice expansion factor $F_a = 1.004$ is based on data from [1], page 156, for stainless steel with T = 290°F. Effects of variation of T within the operating range on F_a were negligible.

Table A1 gives data for correction factor M/M_o as a function of M_o and summarizes calculation for equation A2. These data are basis for figures 3 and 4. Note these figures are useful for manual correction of M_o values output from the computer through the relation $M = (M/M_o)M_o$. However, for computer based calculations, flowrate M would be calculated directly through equation 2 using current values for ρ, Y and C and a procedure as outlined in Section III.6 above. Note, equation A2 above includes effects of correction factors e_{Cc}, e_{Yc}, e_{Fc} and $e_{\rho c}$ and data for these factors are not given separately.

TABLE A1

CORRECTION FACTOR M/M_o

Orifice meter: D = 2.359 in., β = 0.389, corner taps

M_o	h_w	R_D	C	Y	ρ, lb/ft^3				
lb/hr	in. H_2O	x 10^{-3}	–	–	0.0580	.0600	.0620	.0640	.0660
					M/M_o				
3200	105.00	236	0.6013	0.9549	0.898	0.914	0.929	0.944	0.958
2419	60.00	178	.6017	.9742	.917	.933	.948	.963	.978
1767	32.00	130	.6021	.9862	.929	.945	.961	.976	.991
1249	16.00	92	.6026	.9931	.936	.952	.968	.983	1.000
883	8.00	65	.6033	.9966	.941	.957	.973	.988	1.004
765	6.00	56	.6037	.9975	.942	.958	.974	.989	1.005
625	4.00	46	.6040	.9983	.943	.960	.975	.991	1.006
442	2.00	33	.6051	.9990	.946	.962	.978	.993	1.009
312	1.00	23	.6061	.9996	.948	.964	.980	.996	1.011
221	.50	16	.6068	1.000	.949	.966	.981	.997	1.013
159	.26	12	.6078	1.000	.951	.967	.983	.999	1.014

APPENDIX B

RANDOM ERROR CALCULATIONS

Calculations and data are given for random error e_M/M in the flowrate as expressed already in equations 4 and 5:

$$\frac{e_M}{M} = \pm \left[\left(\frac{e_\rho}{2\rho}\right)^2 + \left(\frac{e_{hw}}{2h_w}\right)^2\right]^{1/2} \tag{4}$$

where

$$e_{hw} = \pm \left[\left(e_{th}\right)^2 + \left(e_{A/D}\right)^2 + \left(e_{SL}\right)^2\right]^{1/2} \tag{5}$$

Error e_ρ is the error in the steam density ρ due to uncertainties in the measurements of P and T. These uncertainties are 0.25 psi and 1.5°F respectively. Assuming that the density varies with P/(T + 460) as for an ideal gas, these uncertainties can be combined on an RSS basis to get:

$$\frac{e_\rho}{\rho} = \pm \left[\left(\frac{e_P}{P}\right)^2 + \left(\frac{e_T}{T + 460}\right)\right]^2 \tag{B1}$$

With nominal P = 27 psia and T = 290°F, $\rho = 0.0615$ lb/ft^3 and $e_\rho/\rho = 0.00947$, where $e_P = 0.25$ psi and $e_T = 1.5$°F.

Random error e_{hw} has 3 components as expressed in equation 5; those due to ΔP transmitter hysteresis e_{th}, analog/digital conversion $e_{A/D}$ and sensing line error e_{SL}. Transmitter hysteresis is assigned as a random error because the hysteresis normally depends on the direction of approach (h_w increasing, or h_w decreasing), and this direction is assumed to occur in a random fashion. Transmitter hysteresis is rated on an adjusted span basis as listed in table 5, 0.10 percent of span. Thus, $e_{th} = 0.105$ in. H_2O for the HIGH, and $e_{th} = 0.008$ in. H_2O for the LOW transmitter. Error $e_{A/D}$ was assumed to correspond to ± 1 count (± 1 digit) where 999 counts corresponds to the span of h_w. Thus, $e_{A/D} = 0.105$ and 0.008 in. H_2O for the HIGH and LOW

transmitters, respectively. Error e_{SL} was based on an assumed density difference not exceeding that due to 1°F temperature difference in the condensate in two pressure sensing lines of height 5 feet. Since $\Delta P = \rho gh$, $e_{SL} = \Delta(\Delta P)/\rho_c g = (\Delta\rho_c)h_{SL}/\rho_c$, where the change in ΔP due to the density difference is $\Delta(\Delta P) = (\Delta\rho_c)gh_{SL}$. For water at ambient temperature and h_{SL} = 60 inches, e_{SL} = 0.008 in. H_2O where $\Delta\rho_c$ corresponds to a ΔT of 1°F. Admittedly, this assigned value for e_{SL} is quite arbitrary, and in fact its value is "unknowable". However, it is important to minimize its effect by keeping the two sensing lines short, nearly horizontal, and close together. Under these conditions, it is believed the effect will likely not exceed the assigned value.

With the above values for e_{th}, $e_{A/D}$ and e_{SL}, error e_{hw} becomes 0.149 in. H_2O for the HIGH meter and 0.0139 in. H_2O for the LOW meter.

The above errors as expressed in equation 4 are tabulated in table B1, which gives e_M/M as a function of M_o. These data are plotted on figure 5. They show that for the combined HIGH/LOW meter configuration, the dominating error is e_ρ except at lowest ΔP's for each transmitter, where error e_{hw} dominates. For the HIGH meter alone, the precision error is dominated by error e_{th} = 0.105 in. H_2O (through e_{hw}) for low flowrates up to about 1000 lb/hr. Therefore, when the steam flowrate is essentially constant, the differential pressure transmitter should be selected to operate near full scale. If the steam rate varies through a large range, say greater than 3:1, and depending upon relative operating periods at low flowrates, consideration should be given to use of 2 transmitters, one active at high ΔP and one at low ΔP.

With reference to equation 3, consider random errors in the energy rate E. Errors e_h, e_{Tc} and errors in M (e_M) are all significant. Variations in operating conditions P and T, and T_c are assumed random, and for the range of P and T (26.8 to 27.9 psia and 280 to 299°F, table 4), the corresponding range in h is ± 5 Btu/lb. Thus, for Δh = 1185 - 144 = 1041 Btu/lb, $e_h/\Delta h$ = 0.5 percent. For

the range of T_c from 173 to 179°F, $e_{Tc} = \pm 3$°F and $e_{Tc}(c_p)/\Delta h = 3(1)/1041 =$ 0.3 percent. Errors in P, T and T_c measurements will have minor effect on e_h and e_{Tc}, and are neglected. Referring to figure 4, when $M_n = M_s = 700$ lb/hr for example, $e_M/M = 0.5$ percent and $e_{Mn}/(M_n + M_s) = e_{Ms}/(M_n + M_s) =$ 0.25 percent. Substituting these data into equation 3, $e_M/M = \left[(.25)^2 + (.25)^2 + (.5)^2 + (.3)^2\right]^{1/2} = 0.68$ percent. Larger values of e_M/M will result in less effect of e_h and e_{Tc}. Therefore, random error e_E/E will range upward from about 0.7 percent. Error e_M will control at lowest ΔP values for each transmitter.

TABLE B1

RANDOM ERROR e_M/M

HIGH METER	LOW METER
e_{th} = 0.105 in. H_2O	e_{th} = 0.008 in. H_2O
$e_{A/D}$ = .105	$e_{A/D}$ = .008
e_{SL} = .008	e_{SL} = .008

M_o	h_w	$\frac{e_\rho}{2\rho}$	$\frac{e_{th}}{2h_w}$	$\frac{e_{A/D}}{2h_w}$	$\frac{e_{SL}}{2h_w}$	$\frac{e_{hw}}{2h_w}$	$\frac{e_M}{M}$
lb/hr	in. H_2O	←		percent			→
				HIGH METER			
3200	105.00	0.47	0.05	0.05	0.0	0.07	0.48
2208	50.00	.47	.11	.11	.01	.15	.49
1562	25.00	.47	.21	.21	.02	.30	.56
1082	12.00	.47	.44	.44	.03	.62	.78
788	6.37	.47	.82	.82	.06	1.17	1.26
718	5.28	.47	.99	.99	.08	1.41	1.49
541	3.00	.47	1.75	1.75	.13	2.48	2.53
383	1.50	.47	3.50	3.50	.27	4.96	4.98
271	0.75	.47	7.00	7.00	.53	9.97	9.92
160	.26	.47	20.2	20.2	1.54	28.6	28.6
				LOW METER			
883	8.00	0.47	0.05	0.05	0.05	0.09	0.48
788	6.37	.47	.06	.06	.06	.11	.48
718	5.28	.47	.08	.08	.08	.14	.49
541	3.00	.47	.13	.13	.13	.23	.52
383	1.50	.47	.27	.27	.27	.46	.66
271	0.75	.47	.53	.53	.53	.93	1.04
160	.26	.47	1.54	1.54	1.54	2.67	2.71

APPENDIX C

SYSTEMATIC ERROR CALCULATIONS

Calculations and data are given for systematic error in the flowrate e_{Ms}/M $(e_{Ms,n}/M_n, e_{Ms,s}/M_s)$ as expressed previously in equations 7 and 8:

$$\frac{e_{Ms}}{M} = \pm\left[\frac{e_{Cs}}{c} + \frac{e_{Ys}}{Y} + \frac{2e_{ds}}{d} + \frac{e_{hws}}{2h_w} + \frac{2\beta^3 e_{\beta s}}{1-\beta^4}\right] \tag{7}$$

$$e_{hws} = \pm\left[e_{Ts} + e_{As} + e_{Rs}\right] \tag{8}$$

where

$$e_{As} = \pm\left[e_{As,sp} + e_{As,z}\right] \tag{C1}$$

$$e_{Rs} = \pm\left[e_{Rs,i} + e_{Rs,rp}\right] \tag{C2}$$

Data for the individual errors and systematic error e_{Ms}/M for the HIGH and LOW transmitters are listed in table C1. These data are basis for the systematic error curves shown on figure 6. Following are further explanation and illustrative calculations for these data.

In equation 7, errors e_{Cs} and e_{Ys} are tolerances on the orifice discharge coefficient C and fluid expansion factor Y, respectively, as given in [1]. At low values of h_w (<8 in. H_2O), e_{Ys} can be neglected since fluid expansion (density change) through the orifice is practically nil. Thus, e_{Ys} becomes zero.

Errors e_{ds} and $e_{\beta s}$ are errors assigned due to manufacturing tolerances, since direct measurements of the orifices and pipe were not made. The tolerance in the orifice diameter is 0.0005 inch and $2e_{ds}/d = 2(0.0005)/2.359 = 0.042$ percent. This term is neglected in equation 7. With regard to $e_{\beta s}$, a tolerance of 1.5 percent on pipe ID was assigned as a reasonable estimate after conversations with representatives of the steel industry [5], although ASTM standards A-53 and A-120 allow larger variations. Thus, $e_{Ds}/D = 0.015$ and with $\beta = d/D$

$$e_{\beta s}/\beta = \pm \left[e_{ds}/d + e_{Ds}/D\right] \tag{C3}$$

Since $e_{Ds}/D >> e_{ds}/d$, $e_{\beta s} = 0.015$. Substituting this into term $2\beta^3 e_{\beta s}/(1 - \beta^4)$ of equation 7 yields 0.07 percent, where $\beta = 0.389$. This quantity is neglected in this analysis.

In equation 8, error e_{Ts} is the ΔP transmitter linearity characteristic expressed on an adjusted span basis. Both transmitters are rated 0.35 percent of span and the (limits for bounds of the) systematic error e_{Ts} was assumed not exceeding this figure. For the HIGH meter, 105 in. H_2O span, $e_{Ts} = 0.368$ in. H_2O. For the LOW meter, 8 in. H_2O span, $e_{Ts} = 0.028$ in. H_2O.

Error e_{As} (equation C1) gives the transmitter ambient temperature characteristics with the two components claimed independent by the manufacturer. They are the span shift $e_{As,sp}$ expressed on an adjusted span basis, and the zero shift $e_{As,z}$ expressed on a maximum (upper range limit, URL) span basis. Table 5 lists data for these characteristics. The transmitters operated in an environment 75±15°F and e_{As} data are given on this basis. Using the data from table 5, for the HIGH meter:

$$e_{As,sp} = 0.21\%\ \text{span} = 0.221\ \text{in. } H_2O$$

$$e_{As,z} = .12\%\ \text{URL} = .126\ \text{in. } H_2O$$

and for the LOW meter:

$$e_{As,sp} = 0.26\%\ \text{span} = 0.021\ \text{in. } H_2O$$

$$e_{As,z} = .23\%\ \text{URL} = .090\ \text{in. } H_2O$$

In the above, the range is 15°F, where it is assumed the transmitters are calibrated in an environment at or near 75°F.

Error e_{Rs} estimated for the calibration process has two independent components the error in the transmitted current measurement $e_{Rs,i}$ and the error in the applied reference pressure $e_{Rs,rp}$. For the ΔP transmitters, current output I varies from 4.00 to 20.00 mA for the ΔP range zero to adjusted span h_{wsp}, i. e.

$$I = 4.00 + 16.00\ h_w/h_{wsp} \quad \text{mA} \tag{C4}$$

The error B in the current measurement for the digital multimeter employed is:

$$B = 0.0005\ (I) + 0.0001\ \text{mA} \tag{C5}$$

where 0.001 corresponds to $\pm$ 1 l.s.d. (least significant digit). Scaling B to units of ΔP, $e_{Rs,i}$ becomes $(h_{wsp})(B/16)$ in. H_2O and substituting equations C4 and C5,

$$e_{Rs,i} = \pm \left[0.003(h_{wsp}/16) + 0.0005(h_w)\right] \text{ in } H_2O \tag{C6}$$

For both transmitters, error $e_{Rs,rp}$ is based on vertical manometry techniques using water or mercury, with ΔP assumed read to $\pm$ 0.5 mm, i.e., $e_{Rs,rp} = \pm\ 0.028$ in. H_2O. Some improvement could be realized through use of inclined or micro-manometry methods (LOW transmitter), reading to perhaps 0.005 in. H_2O or better.

TABLE C1

SYSTEMATIC ERROR e_{Ms}/M

HIGH METER

span h_{wsp} = 105 in. H_2O

e_{Ts} = 0.368 in. H_2O

$e_{As,sp}$ = 0.221

$e_{As,z}$ = 0.126

LOW METER

span h_{wsp} = 8.00 in. H_2O

e_{Ts} = 0.028 in. H_2O

$e_{As,sp}$ = 0.021

$e_{As,z}$ = 0.090

e_{Rs} = $0.028 + (h_{ws}/16)(0.003) + 0.0005h_w$, both transmitters

M_o	hw	$\frac{e_{Ts}}{2h_w}$	$\frac{e_{As,sp}}{2h_w}$	$\frac{e_{As,z}}{2h_w}$	$\frac{e_{Rs}}{2h_w}$	$\frac{e_{hw}}{2h_w}$	$\frac{e_C}{C}$	$\frac{e_Y}{Y}$	$\frac{e_{Ms}}{M}$
lb/hr	in. H_2O	← Percent →							
		HIGH METER							
3200	105.00	0.18	0.11	0.06	0.05	0.40	1.00	0.25	1.65
2208	50.00	.37	.22	.13	.07	.79	1.00	0.25	2.04
1562	25.00	.74	.44	.25	.12	1.55	1.00	0.25	2.80
1082	12.00	1.53	.92	.53	.22	3.20	1.00	0.25	4.45
788	6.37	2.89	1.73	.99	.40	6.01	1.00	0.0	7.01
718	5.28	3.48	2.09	1.19	0.47	7.23	1.00	0.0	8.23
541	3.00	6.13	3.68	2.10	.83	12.7	1.00	0.0	13.7
383	1.50	12.3	7.37	4.20	1.67	25.5	1.00	0.0	26.5
271	0.75	25.5	14.7	8.40	3.33	51.9	2.00	0.0	53.9
160	.26	70.8	42.5	24.2	9.23	147.0	2.00	0.0	149.0
		LOW METER							
883	8.00	0.18	0.13	0.56	0.21	1.08	1.00	0.0	2.08
788	6.37	.22	.16	.71	.26	1.35	1.00	0.0	2.35
718	5.28	.27	.20	.85	.30	1.62	1.00	0.0	2.62
541	3.00	.47	.35	1.50	.52	2.84	1.00	0.0	3.84
383	1.50	.93	.70	3.00	1.00	5.63	1.00	0.0	6.63
271	0.75	1.87	1.40	6.00	1.99	11.3	2.00	0.0	13.3
160	.26	5.38	4.04	17.3	5.70	32.4	2.00	0.0	34.4

APPENDIX D

TABLE OF NOMENCLATURE

Symbol	Description	Dimensions *
A	Observed count, output from differential pressure A/D converter	----
A_s	Uncertainty in accumulated energy usage, bounds to the systematic error	----
C	Coefficient of discharge for the orifice meter	----
c_p	Specific heat of condensate	Btu/(lb·°F)
D	Pipe inside diameter	in.
d	Diameter of orifice	in.
E	Net energy rate	Btu/hr
$e_{A/D}$	Random error, analog/digital conversions, computer system	in. H_2O
e_{As}	Systematic error, ΔP transmitter, ambient temperature zero and span shift error	in. H_2O
$e_{As,sp}$	Systematic error, ΔP transmitter, ambient temperature, span shift component	in. H_2O
$e_{As,z}$	Systematic error, ΔP transmitter, ambient temperature, zero shift component	in. H_2O
e_{Cc}	Correction factor, orifice discharge coefficient	----
e_{Cs}	Systematic error (tolerance), assigned to discharge coefficient C	----
e_{ds}	Systematic error, manufacturing tolerance for d	in.
e_{Ds}	Systematic error, manufacturing tolerance for D	in.
e_E	Random error in energy rate E	Btu/hr
e_{Es}	Systematic error in energy rate E	Btu/hr
e_{Fc}	Correction factor, orifice thermal expansion	----
e_h	Random error in enthalpy h	Btu/lb
e_{hw}	Random error in differential pressure hw	in. H_2O
e_{hws}	Systematic error in hw	in. H_2O

*Note: All quantities denoted in. H_2O refer to inches of water at 68°F. Symbol "lb" refers to pound mass.

Symbol	Description	Dimensions
e_{Mn}	Random error in flowrate Mn	lb/hr
e_{Ms}	Random error in flowrate Ms	lb/hr
$e_{Ms,n}$	Systematic error in flowrate Mn	lb/hr
$e_{Ms,s}$	Systematic error in flowrate Ms	lb/hr
e_P	Random error in supply steam pressure P	psi
e_{Rs}	Systematic error in applied reference pressure and transmitter current measurement	in. H_2O
$e_{Rs,i}$	Systematic error, due to ΔP transmitter current measurement	in. H_2O
$e_{Rs,rp}$	Systematic error, ΔP transmitter reference pressure	in. H_2O
e_{SL}	Random error, allowance for possible density variations in pressure sensing lines	in. H_2O
e_T	Random error in supply steam temperature T	°F
e_{Tc}	Random error in condensate temperature Tc	°F
e_{th}	Random error, ΔP transmitter hysteresis	in. H_2O
e_{Ts}	Systematic error, ΔP transmitter linearity	in. H_2O
e_{Yc}	Correction factor, steam expansion	----
e_{Ys}	Systematic error (tolerance) assigned to expansion factor Y	----
$e_{\beta s}$	Systematic error in β ratio due to manufacturing tolerance in d and D	----
e_{ρ}	Random error in density ρ due to uncertainty in P and T measurement	lb/ft^3
$e_{\rho c}$	Correction factors, steam density variation with P and T	----
F_a	Area factor for thermal expansion of the orifice	----
g	Local acceleration of gravity	ft/s^2
h	Enthalpy of supply steam	Btu/lb
h_w	Differential pressure	in. H_2O
h_{wsp}	Differential pressure transmitter adjusted span value	in. H_2O
K	Scaling constant, differential pressure transmitter	lb/hr
M_n	Mass flowrate, north branch meter	lb/hr
M_o	Observed or indicated mass flowrate	lb/hr

Symbol	Description	Dimensions
M_s	Mass flowrate, south branch meter	lb/hr
P	Pressure of supply steam	psia
R_D	Pipe Reynolds number = $48M/3600\pi D\mu$	----
T	Temperature of supply steam	°F
T_c	Temperature of condensate	°F
T_s	Steam saturation temperature at pressure P	°F
Y	Steam expansion factor	----
β	Ratio d/D	----
γ	specific heat ratio, $c_p/c_v = 1.3$ for steam	----
Δh	Net enthalpy change = $h - c_p(T_c - 32.0)$	Btu/lb
ΔP	Differential pressure	psi
ρ	Density	lb/ft^3
ρ_c	Density of condensate in ΔP sensing legs	lb/ft^3
μ	Absolute viscosity of steam	lb/ft•s

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Some important design features and measurement techniques are discussed for determining energy rates in building systems flowing steam. Emphasis is on use of differential pressure (ΔP) type flowmeter systems where ΔP, pressure and temperature instrumentation only can receive direct calibration. The role of systematic and random type errors in measurement of building energy is discussed and an appropriate method is given for estimating the uncertainty in the energy consumed. An example calculation of uncertainty in accumulated energy used for a 1 year period is given from typical operating data for one of the NBS laboratory buildings. The uncertainty is estimated to be 3.2% for a two-meter (series) configuration and 4.3% for a single meter (high range meter) configuration.

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Building energy monitoring; energy measurement; steam consumption measurement; uncertainty estimate.

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